

The long and the short of the high energy emission in GRB090926A: an external shock

J. R. Sacahui¹, N. Fraija¹, M. M. González¹ and W. H. Lee¹

Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 70-264,
Cd. Universitaria, México DF, 04510

jsacahui@astro.unam.mx, nifraiya@astro.unam.mx, magda@astro.unam.mx,
wlee@astro.unam.mx

Received _____; accepted _____

ABSTRACT

SSC emission from a reverse shock has been suggested as the origin for the high energy component lasting 2 s in the prompt phase of GRB98080923 (Fraija et al. 2012). The model describes spectral indices, fluxes and the duration of the high-energy component as well as a long keV tail present in the prompt phase of GRB980923. Here, we present an extension of this model to describe the high-energy emission of GRB090926A. We argue that the emission consist of two components, one with a duration less than 1s during the prompt phase, and a second, longer-lasting GeV phase lasting hundred of seconds after the prompt phase. The short high-energy phase can be described as SSC emission from a reverse shock similar to that observed in GRB980923, while the longer component arises from the forward shock. The main assumption is that the jet is magnetized and evolves in the thick-shell case, and the calculated fluxes and break energies are all consistent with the observed values. A comparison between the resulting parameters obtained for GRB980923 and GRB090926A suggests differences in burst tails that could be attributable to the circumburst medium, and this could account for previous analyses reported in the literature for other bursts. We find that the density of the surrounding medium inferred from the observed values associated to the forward shock agrees with standard values for host galaxies such as the one associated to GRB090926A.

Subject headings: gamma ray: burst — radiation mechanism: nonthermal

1. Introduction

High-energy gamma-ray emission from IC and SSC processes in different locations of a relativistic jet have been widely explored as a source for the observed high-energy emission in gamma-ray bursts. Considering electrons accelerated in external (as the jet interacts with the circumburst medium) and internal (within the jet as the Lorentz factor of the flow varies) shocks and different photon populations, IC emission has been discussed in detail in GRB internal shocks (Papathanassiou & Meszaros 1996; Pilla & Loeb 1998; Panaitescu & Meszaros 2000), forward shocks (Sari et al. 1996; Totani 1998; Waxman 1997; Panaitescu & Meszaros 1998; Wei & Lu 1998; Chiang & Dermer 1999; Dermer et al. 2000a,b; Panaitescu & Kumar 2000) and reverse shocks (Wang et al. 2001a,b; Pe’er & Wijers 2006). On the other hand, SSC processes from forward (Sari et al. 2001; Wang et al. 2001a) and reverse shocks (Granot & Guetta 2003; Wang et al. 2001a,b) have been investigated separately to explain some atypical high energy components. Also, the high-energy gamma-ray emission has been described using afterglow synchrotron radiation with a sufficiently low ISM density (Liu & Wang 2011; He et al. 2011).

Recently, Fraija et al. (2012) proposed that the smooth tail and the high-energy component present in GRB980923 can be explained in a unified manner with a SSC reverse and forward shock model. While the smooth tail comes from forward shock synchrotron emission, the high-energy component arises from synchrotron self-Compton (SSC) from the reverse shock. In order to unify both processes Fraija et al. (2012) considered different equipartition parameters for the reverse and forward shocks ($\epsilon_{B,r} \neq \epsilon_{B,f}$ and $\epsilon_{e,r} \neq \epsilon_{e,f}$), thus leading to the requirement that the ejecta has to be highly magnetized. This assumption has been considered before, as in the work by Kumar & Panaitescu (2003) for GRB 021211.

We note that in previous work, Kumar & Barniol-Duran (2009, 2010) and

Ghisellini et al. (2010) have explored how synchrotron radiation from a forward shock could account for long lasting high energy emission, finding good evidence in support of this model for a number of GRBs detected by the Fermi high energy detector (LAT). More recently, Veres & Meszaros (2012) investigated possible scenarios to obtain more than one observable component detected in the LAT energy range. They explored SSC processes from forward and reverse shocks as possible mechanisms to produce the high-energy emission, and concluded that depending on the equipartition parameters ($\epsilon_{B,r} = \epsilon_{B,f}$ and $\epsilon_{e,r} = \epsilon_{e,f}$), one or the other could develop to explain the energy component detected by LAT, besides requiring a population of photons from the prompt emission.

Here we extend the model used for GRB980923, showing that only the assumption of a magnetized jet is required to explain the complete high-energy emission with an SSC reverse and forward shock model. We also discuss the implications of the results with respect to the circumburst medium.

2. GRB 090926A

GRB 090926A was reported as a bright and long gamma-ray burst, observed by Fermi LAT/GBM (Ackermann et al. 2010) at 04:20:26.99 (UT) on 26 September 2009. The GBM triggered on and localized it at RA=354.5° and Dec=-64.2° in J2000 coordinates. GRB090926A was localized at $\approx 52^\circ$ with respect to the pointing/axis direction and well within the field of view of Fermi. It was independently detected by INTEGRAL SPI-ACS (Bisaldi 2009), Suzaku/WAM (Noda et al. 2009), CORONAS-PHOTON (Chakrabarti et al. 2009) and the Konus-wind experiment (Golenetskii et al. 2009). The lightcurve observed by Konus-wind shows a prompt phase of 16 s followed by a weak tail up to $\sim T_0 + 50$ s, and Suzaku WAM and CORONAS-PHOTON report a tail of similar energy range and duration.

Based upon the GCN report of the LAT detection, an observation by the Swift XRT and UVOT was performed and an afterglow was detected at T_0+47 ks. Skynet/PROMPT also detected an optical afterglow emission 20 hr post burst (Noda et al. 2009). VLT observations using the X-shooter spectrograph determined a redshift of $z=2.1062$ (Malesani, et al. 2009) and concluded that the host galaxy associated with this burst was a dwarf irregular galaxy with one of the lowest metallicities observed for a GRB host galaxy (D’Elia et al. 2010), $[X/H] = 3.2 \times 10^{-3} - 1.2 \times 10^{-2}$ with respect to solar.

Joint LAT and GBM data analysis concluded that GRB090926A presents a distinct high energy power law component separated from the known BAND function (Ackermann et al. 2010). The burst is fit by a Band+CUTPL function with a high energy spectral break at $E_f = -1.41^{+0.22}_{-0.42}$ GeV and with a power law index of $-1.72 \pm^{+0.10}_{-0.02}$. The fit was made for several time episodes noting that the extra power law component is very significant in one short episode lasting 0.15 s and in the subsequent episodes. The short episode is in coincidence with a sharp spike apparent in the light curve above 100 MeV at $\sim t_0 + 10$ s. Ackermann et al. (2010) described this short peak through a power law with a cutoff energy and obtained a value for the cutoff energy of $E_f = 0.40^{+0.13}_{-0.06}$ stat. ± 0.05 syst. GeV. The flux between 10 keV and 10 GeV for this short episode is $22.29 \pm 1.60 \times 10^{-6}$ erg cm $^{-2}$ s $^{-1}$ and the power law index is $\lambda = -1.71^{+0.02}_{-0.05}$. After the short spike the burst is better described by a Band+PL function with a power law index of $\lambda = -1.79 \pm 0.03$ and a flux of $5.83 \pm 0.30 \times 10^{-6}$ erg. Using the results of the Band+CUTPL model, Ackermann et al. (2010) inferred an isotropic energy for this burst of $E_{iso} = 2.24 \pm 0.04 \times 10^{54}$ erg in agreement with the value reported by Golenetskii et al. (2009).

Given the similarities, and relevant differences between the two bursts cited, we summarize in Table 1 the relevant observational parameters for both GRB090926A and GRB980923. The presence of a short peak with high energy emission within the prompt

phase in both events is remarkable. We thus investigate the possibility of explaining the long duration emission at the highest energies with an extension of the model previously used for GRB980923 (Fraija et al. 2012).

Parameter	GRB980923	GRB090926A
T_{90}	32 s	20 s
Duration of the High energy component	< 2s	< 1 s
Spectral index of the tail (keV)	2.4	-
Spectral index of the short high component	-1.44 ± 0.07 González et al. (2011)	$-1.71^{+0.02}_{-0.05}$
Isotropic Energy (erg)	-	2.2×10^{54}
Redshift	-	2.1096
Energy range of the tail	~ 100 keV	~ 50 keV (Golenetskii et al. 2009)
Range of the short high energy component	> 200 MeV	> 400 MeV
Range of the long high energy component	-	~ 10 GeV

Table 1. Observed parameters for GRB980923 and GRB090926A

3. Dynamics of the External Shocks

3.1. Long GeV Component from Forward Shock

For the forward shock, we assume that electrons are accelerated in the shock to a power law distribution of Lorentz factors γ_e , with a minimum Lorentz factor γ_m : $N(\gamma_e)d\gamma_e \propto \gamma_e^{-p}d\gamma_e$, where $\gamma_e \geq \gamma_m$ and $\epsilon_{e,f}$ and $\epsilon_{B,f}$ are the constant fractions of the shock energy that is transferred into the electrons and the magnetic field, respectively. Then

$$\begin{aligned}
 \gamma_{m,f} &= \epsilon_{e,f} \left(\frac{p-2}{p-1} \right) \frac{m_p}{m_e} \gamma_f \\
 &= 524.6 \epsilon_{e,f} \gamma_f
 \end{aligned} \tag{1}$$

where we assume a typical value of p for a synchrotron forward emission of $p = 2.4$, as observed in GRB980923 by Giblin et al. (1999) and generally assumed in Veres & Meszaros (2012). Adopting the notation of Sari et al. (1998) we compute the typical and cooling frequencies of the forward shock synchrotron emission (Sari et al. 1998) which are given by,

$$\begin{aligned} E_{\text{m,f}} &\sim 10.13 \left(\frac{1+z}{3} \right)^{-1} \epsilon_{e,f,-1}^2 \epsilon_{B,f,-4.3}^{1/2} n_{f,1}^{1/2} \gamma_{f,600}^4 \text{ keV} \\ E_{\text{c,f}} &\sim 141.7 \left(\frac{1+z}{3} \right)^{-1} \left(\frac{1+x_f}{11} \right)^{-2} \epsilon_{B,f,-4.3}^{-3/2} n_{f,1}^{-5/6} E_{54}^{-2/3} \gamma_{f,600}^{4/3} \text{ eV} \\ F_{\text{max,f}} &\sim 3.8 \times 10^{-2} \left(\frac{1+z}{3} \right) \epsilon_{B,f,-4.3}^{1/2} n_{f,1}^{1/2} D_{28.3}^{-2} E_{54} \text{ Jy} \\ t_{\text{tr,f}} &\sim 467.5 \left(\frac{1+z}{3} \right) \left(\frac{1+x_f}{11} \right)^2 \epsilon_{e,f,-1}^2 \epsilon_{B,f,-4.3}^2 n_{f,1} E_{54} \text{ s} \end{aligned} \quad (2)$$

where the convention $Q_x = Q/10^x$ has been adopted in cgs units throughout this document unless something else is specified. $t_{\text{tr,f}}$ is the transition time when the spectrum changes from fast cooling to slow cooling, D is the luminosity distance, n_f is the ISM density, E is the energy, the term $(1+x_f)$ was introduced because a once-scattered synchrotron photon generally has energy larger than the electron mass in the rest frame of the second-scattering electrons. Multiple scattering of synchrotron photons can be ignored. x_f is given by Sari et al. (2001) as:

$$x_f = \begin{cases} \frac{\eta \epsilon_{e,f}}{\epsilon_{B,f}}, & \text{if } \frac{\eta \epsilon_{e,f}}{\epsilon_{B,f}} \ll 1, \\ \left(\frac{\eta \epsilon_{e,f}}{\epsilon_{B,f}} \right)^{1/2}, & \text{if } \frac{\eta \epsilon_{e,f}}{\epsilon_{B,f}} \gg 1. \end{cases} \quad (3)$$

where $\eta = (\gamma_{\text{c,f}}/\gamma_{\text{m,f}})^{2-p}$ for slow cooling and $\eta = 1$ for fast cooling.

From eq. 2, we observe directly that $\nu_{\text{m,f}} \gg \nu_{\text{c,f}}$, the break energy $E_{\text{m,f}} \sim 10.13 \text{ keV}$ and $t_{\text{tr,f}} \sim 467.5 \text{ s}$ implying that the synchrotron emission could be observed in the fast cooling regime within a hundred of seconds from the burst. Thus, if $E_{\text{peak}}(t) = E_0(t-t_0)^{-\delta}$, then $\delta \sim 1.5$ (Zhang et al. 2007)

$$\begin{aligned}
E_{\text{m,f}}^{(IC)} &\sim 9.15 \left(\frac{1+z}{3}\right)^{5/4} \epsilon_{e,r,-1}^4 \epsilon_{B,f,-4.3}^{1/2} \gamma_{f,600}^4 n_{f,1}^{-1/4} E_{54}^{3/4} t_{f,2}^{-9/4} \text{ GeV} \\
E_{\text{c,f}}^{(IC)} &\sim 18.4 \left(\frac{1+z}{3}\right)^{-3/4} \left(\frac{1+x_f}{11}\right)^{-4} \epsilon_{B,f,-4.3}^{-7/2} n_{f,1}^{-9/4} E_{54}^{-5/4} t_{f,2}^{-1/4} \text{ eV} \\
F_{\text{max,f}}^{(IC)} &\sim 1.59 \times 10^{-4} \left(\frac{1+z}{3}\right)^{3/4} \epsilon_{B,f,-4.3}^{1/2} n_{f,1}^{1/4} D_{28.3}^{-2} E_{54}^{5/4} t_{f,2}^{1/4} \text{ Jy}
\end{aligned} \tag{4}$$

From eq. 4 we observe that the break energies and $(\nu F)_{\text{max}} = 10.9 \times 10^{-7} \text{ erg cm}^2 \text{ s}^{-1}$ are consistent with the values given by Ackermann et al. (2010).

3.2. Hard component from thick shell Reverse Shock

Following the formalism of Fraija et al. (2012) with the appropriated values for GRB090926A, we obtain for the synchrotron contribution,

$$\begin{aligned}
E_{\text{m,r}} &\sim 165.04 \left(\frac{1+z}{3}\right)^{-1} \left(\frac{\epsilon_{e,r}}{0.65}\right)^2 \left(\frac{\epsilon_{B,r}}{0.125}\right)^{1/2} \gamma_{r,3}^2 n_{r,1}^{1/2} \text{ eV} \\
E_{\text{c,r}} &\sim 1.1 \times 10^{-3} \left(\frac{1+z}{3}\right)^{3/2} \left(\frac{1+x+x^2}{6}\right)^{-2} \left(\frac{\epsilon_{B,r}}{0.125}\right)^{-7/2} n_{r,1}^{-3} E_{54}^{-1/2} \gamma_{r,3}^{-6} \left(\frac{T_{90}}{20s}\right)^{5/2} \text{ eV} \\
F_{\text{max,r}} &\sim 3.4 \times 10^2 \left(\frac{1+z}{3}\right)^{7/4} \left(\frac{\epsilon_{B,r}}{0.125}\right)^{1/2} n_{r,1}^{1/4} D_{28.3}^{-2} E_{54}^{5/4} \gamma_{r,3}^{-1} \left(\frac{T_{90}}{20s}\right)^{-3/4} \text{ Jy}
\end{aligned} \tag{5}$$

and for the SSC contribution,

$$\begin{aligned}
E_{\text{m,r}}^{(IC)} &\sim 414.3 \left(\frac{1+z}{3}\right)^{-7/4} \left(\frac{\epsilon_{e,r}}{0.65}\right)^4 \left(\frac{\epsilon_{B,r}}{0.125}\right)^{1/2} \gamma_{r,3}^4 n_{r,1}^{3/4} E_{54}^{-1/4} \left(\frac{T_{90}}{20s}\right)^{3/4} \text{ MeV} \\
E_{\text{c,r}}^{(IC)} &\sim 0.7 \times 10^{-5} \left(\frac{1+z}{3}\right)^{3/2} \left(\frac{1+x+x^2}{6}\right)^{-4} \left(\frac{\epsilon_{B,r}}{0.125}\right)^{-7/2} n_{r,1}^{-3} E_{54}^{-1/2} \gamma_{r,3}^{-6} \left(\frac{T_{90}}{20s}\right)^{-5/2} \text{ eV} \\
F_{\text{max,r}}^{(IC)} &\sim 2.6 \times 10^{-1} \left(\frac{1+z}{3}\right)^{9/4} \left(\frac{\epsilon_{B,r}}{0.125}\right)^{1/2} n_{r,1}^{3/4} D_{28.3}^{-2} E_{54}^{7/4} \gamma_{r,3}^{-2} \left(\frac{T_{90}}{20s}\right)^{-5/4} \text{ Jy}.
\end{aligned} \tag{6}$$

From eq. 6 we observe that the break energies and $(\nu F)_{\text{max}} = 8.2 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1}$ are again consistent with the values given by Ackermann et al. (2010) and quoted above in

§ 3.1. They also are similar to the ones obtained for GRB980923 as well as the values of $\epsilon_{f,e,B}$ and densities n_f . In fact, the ability to describe the short high energy emission from the reverse shocks depends mainly on the value of the equipartition parameters. We can interpret this as a requirement of a highly magnetized jet, and deal with the density in what follows.

4. Discussion and conclusions

We have presented a model that describes both the short and long high energy components of GRB090926A. The parameters used to describe the short high-energy component are similar to the ones found for GRB980923, as expected because of the similarities in the emission parameters (mainly duration, lightcurve and spectral index) for both bursts. For this component, our model is very dependent on the values of $\epsilon_{B,r} = 0.125$ and $\epsilon_{e,r} = 0.65$, and implies the presence of a highly magnetized jet. We note that numerical particle in cell simulations carried out by Sironi & Spitkovsky (2011) appear to limit the magnetization parameter to $\sigma \simeq \epsilon_B/10 \leq 10^{-3}$. However, these simulations have not been run for a long enough time to rule out if electrons can be accelerated for high magnetization shocks. Moreover, studies of other GRB events (Mészáros & Rees 2011; Barniol-Duran & Kumar 2011; Ghisellini et al. 2010) with external shocks have found similar values to those reported here to be consistent with observations.

The tail of the prompt emission of GRB980923 is described in our model as synchrotron radiation from the forward shock at energies of hundreds of keVs. This means that if an SSC component is present, it would appear at energies greater than tens of TeVs, which would not explain the long high-energy component observed in GRB090926A. However, it was found that SSC emission can account for the long high-energy component of GRB090926A with similar values for the equipartition parameters as in GRB980923, but with a higher

circumburst density.

To complement the information intrinsic to the prompt high energy emission, we have roughly estimated the ambient density within the host using typical parameters for a dwarf galaxy ($L \sim 300$ pc) and the column densities reported by D’Elia et al. (2010) and Rau et al. (1996), obtaining $n = 8.85$ and 11.93 cm^{-3} , respectively. These values are consistent with the value required by our model.

The duration of the long high-energy component is estimated as the time for which $E_{f,m}^{IC}$ decreases below 2 GeV, obtaining a value of ≈ 100 s, in agreement with FERMI observations. Moreover, the keV-tail observed by Golenetskii et al. (2009) can be related to the expected long (hundred of seconds) keV-component resulting from the forward synchrotron emission. One more difference in the tails of GRB090926A and GRB980923 besides the energy range, is their cooling regime, fast or slow respectively. Thus, if these two bursts are representatives of different surrounding media, as the value of n indicates, there should be bursts with long tails in fast cooling regime at energies of a few keV and with long tails in slow cooling regime at energies of hundreds of keV. Coincidentally, Zhang et al. (2007) and Connaughton (2002) have studied tails of bursts observed by SWIFT and BATSE, respectively. Zhang et al. (2007) found single-peaked tails with cutoff energy evolving in time as $E = E_0(\frac{t-t_0}{t_0})^{-\alpha}$ where $\alpha = 1.2 - 1.4$, while Connaughton (2002) describes the temporal decay of the averaged tail of 400 bursts as a power law with index of $\alpha = 0.6$. Both studies are in agreement with our result. Also, the afterglow reported 22 hours after the burst (D’Elia et al. 2010) can be explained as the evolution in time of the synchrotron contribution.

The solution for the forward shock case given in this work is not unique. There are two more cases (Veres & Meszaros 2012; Liu & Wang 2011; He et al. 2011) with similar equipartition parameters but different density values. When $n = 1 \text{ cm}^{-3}$, the long

high-energy component is described by forward SSC, but the duration of the keV-tail has to be longer than the transition time, which in this case is of the order of a day, much longer than the observed by Golenetskii et al. (2009). The second case is when $n = 10^{-4} \text{ cm}^{-3}$, then the long high-energy component is described by forward synchrotron, thus no tail at keV is expected. We note that bursts with a short duration high energy emission as observed in GRB980923 and GRB090926A are candidates to present optical flashes (Sari & Piran 1999a,b) as well as being detected by very-high gamma-ray observatories with wide-field of view as HAWC (Abeysekara et al. 2012).

In summary, we have presented an SSC emission and forward shock model to explain the high energy emission observed in GRB090926A. The presence of tails in the keV regime, their duration, and time evolution are consistent with the reported observations. According to our model, both the short and hard high energy emission within the prompt phase can be interpreted as a signature of the magnetization of the jet, while the energy regime of a long lasting (hundred of seconds) high energy emission would provide an indication of the circumburst medium through the density, with a possible correlation to the host galaxy type.

This work is partially supported by DGAPA-UNAM grant IN105211 and CONACyT grants 105033 and 103520.

REFERENCES

- Abeysekara, A.U. et al., 2012, *Astropart. Phys.*, in press, ArXiv e-prints 1108.6034
- Ackermann, et al. 2010, *ApJ*, 1178, 716
- Barniol-Duran, R., & Kumar, P., 2011 *MNRAS*, 417, 1584
- Bisaldi, E. 2009, *GRB Coordinates Network*, 9933, 1
- Chakrabarti, S. K., et al. 2009, *GRB Coordinates Network*, 10009, 1
- Chiang J. & Dermer C. D. 1999 *ApJ*, 512, 699
- Connaughton V., 2002, *ApJ*, 567, 1028.
- D’Elia, et al., 2010, ArXiv e-prints, 1007.5337
- Dermer C. D., Bottcher M. & Chiang 2000a *ApJ*, 537, 255
- Dermer C. D., Chiang J. & Mitman K.E. 2000b *ApJ*, 537, 785
- Fraija N., Gonzalez M. M., Lee W. H. 2012, ArXiv e-prints, 1201.3689
- Ghisellini, G., Ghirlanda, G., Nava, L., & Celotti, A. 2010, *MNRAS*, 403, 926
- Giblin, T. W., et al. 1999, *ApJ*, 524, L47
- González et al. 2011, *ApJ*, submitted
- Golenetskii, S. et al. 2009, *GRB Coordinates Network*, 9959, 1
- Granot, J. & Guetta, D. 2003, *ApJ*, 598, L11
- He H., et al., 2011, ArXiv e-prints, 1009.1432
- Kumar, P., & Barniol-Duran, R., 2009, *MNRAS*, 400, L75

Kumar, P., & Barniol-Duran, R., 2010, MNRAS, 409, 226

Kumar, P., & Panaitescu, A. 2003, MNRAS, 346, 905

Liu R. & Wang X. 1998 ApJ, 730, 1

Malesani, D., et al. 2009, GRB Coordinates Network, 9942, 1

Mészáros, P., & Rees, M. 2011, ApJ, 40, L733

Noda, K., et al. 2009, GRB Coordinates Network, 9942, 1

Panaitescu A., & Meszaros P. 1998 ApJ, 501, 772

Panaitescu A., & Meszaros P. 2000 ApJ, 544, L17

Panaitescu A., & Kumar P. 2000 ApJ, 543, L66

Papathanassiou H., & Meszaros P. 1996 ApJ, 471, L91

Pilla R. & Loeb A., 1998 ApJ, 494, L167

Pe’er A. & Wijers R. 2006 ApJ, 643, 1036

Rau, A. et al. 2010, ApJ, 720, 862

Sari, R., & Piran, T. 1999a, A&AS, 138, 537

Sari, R., & Piran, T. 1999b, ApJ, 520, 641

Sari, R., Piran, T. & Narayan R. 1998, ApJ, 497, L17

Sari R. & Esin A. A. 2001 ApJ, 548, 787

Pilla R. & Loeb A., 1998 ApJ, 494, L167

Sari, R., Narayan & R. Piran, T. 1996, ApJ, 473, 204

Sironi, L., & Spitkovsky, A., 2011, ApJ, 726, 75

Totani, T. 1998, ApJ, 502, L13

Veres P. & Meszaros P., 2012, ArXiv e-prints, 1202.2821

Waxman E., 1997, ApJ, 489, L33

Wang, X. Y., Dai, Z. G. & Lu, T. 2001a, ApJ, 546, L33

Wang, X. Y., Dai, Z. G. & Lu, T. 2001b, ApJ, 556, 1010

Wei D. M. & Lu T. 1998 ApJ, 505, 252

Wei D. M. & Lu T. 2000 A&A, 360, L13

Wei D. M. & Lu T. 1998 ApJ, 505, 252

Zhang B.B., Liangand E. W. & Zhang B., 2007, ApJ, 666, 1002